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The shrinkage and swelling behaviour of UK soils: the clays of the Lambeth Group

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The shrinkage and swelling behaviour of UK soils: the clays of the Lambeth Group

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Shrinkage cracks in the Gault clay

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Foreword

This is the final interpretative report covering the shrinkage and swelling properties of the Reading and Woolwich formations of the Lambeth Group. It is based on the results of geotechnical tests on ten samples obtained from seven sites across southern England. The study of the Lambeth Group is the third phase of the BGS project entitled 'The shrinkage and swelling behaviour of UK clay soils', the first two having dealt with the Gault (Clay) Formation and mudstones of the Mercia Mudstone Group. The project shares many complementary aspects with the BGS project entitled 'The engineering geology of UK rocks and soils' and to date has dealt with the same formations.

Contents

Executive summary

The report describes work carried out in the geotechnical laboratories of the BGS at Keyworth. A limited number of undisturbed samples were collected from outcrops of the Reading and Woolwich formations of the Lambeth Group at locations in England by taking hand-prepared block samples and tube samples. A variety of geotechnical laboratory tests, measuring shrinkage and swelling both directly and indirectly, were carried out. These included both standard tests and new methods, based on experimental research work, and included tests on both undisturbed and remoulded specimens. The report describes the results of these tests, compares them with the results of geotechnical index tests and mineralogical analyses, and examines the shrink/swell classification of formations within the Lambeth Group. Where appropriate, comparisons are made with data obtained for the Gault Formation and Mercia Mudstone Group previously reported on.

Swelling and shrinkage are two mechanical properties of a soil, which though driven by related physico-chemical mechanisms, are usually treated separately in the laboratory. Swelling sensu stricto is mainly a function of the clay minerals present in the soil or rock. The engineering phenomena of **heave** and **subsidence** may be caused by factors other than swelling and shrinkage of clays, respectively, for example, by stress relief, dissolution etc. The geological processes affecting swelling and shrinkage were reviewed by Gostelow (1995). Usually, the assessment of swelling and shrinkage does not involve direct measurement, but rather indirect estimation of volume change **potential** from index tests on reworked samples. There has been little change over the years to the shrink/swell tests that are described in British Standards. Three shrinkage tests are described in BS1377 (BSI, 1990), two for shrinkage limit and one for linear shrinkage. Both shrinkage limit tests make use of mercury. The two simple swelling tests in BS1377 (BSI, 1990) are based on the oedometer apparatus and measure swelling pressure (surcharge) and swelling strain (no surcharge). A swelling test is also incorporated in the compaction test procedure.

The wide variety of test methods described in the literature was referred to by Hobbs and Jones (1995). In most cases, laboratory tests may be carried out on either **undisturbed** or **disturbed** samples. Undisturbed samples are as near to their in situ condition as possible, whereas disturbed samples may be reworked, reconstituted, or compacted depending on the engineering application. Swelling tests usually either measure the **strain** due to swelling, resulting from access of a partially saturated sample to water, or the **pressure** produced when the sample is restrained from swelling using some form of surcharge. Swelling strain samples may be disc-shaped oedometer types for 1D testing of soils and slaking rocks, or cubes for 3D testing of non-slaking rocks. The 1D samples are laterally restrained. Swelling pressure samples are usually oedometer discs and may be mounted in a normal oedometer or a special swelling pressure apparatus. There are two types of shrinkage test specified in BS1377 (BSI, 1990). These are the shrinkage limit test (of which there are two versions), carried out on undisturbed or disturbed samples, and the linear shrinkage test, carried out on reworked soil paste (prepared as for Atterberg limits). It should be noted that the shrinkage limit is a specific **water content** below which little or no volumetric shrinkage occurs, whereas the linear shrinkage is a percentage reduction in **length** (strain) on oven drying.

The Lambeth Group is generally considered to be of low to medium swell/shrink potential depending on lithology and mineralogy. A variety of tests were carried out on undisturbed samples of the Reading Formation, Mottled Clay Member from various locations. The results found a good positive correlation between 1D swelling strain, ε_{1D} , and swelling pressure, Psw(1) as follows:

$$\varepsilon_{1D} = 0.09.P_{sw(1)} + 2.2 \qquad (r^2 = 0.92)$$

The tests have also shown that the laterally confined vertical swelling strains (1D swelling strain test) are typically between 1 and 2 times unconfined maximum vertical swelling strains (3D cube test). Volumetric swell strain ranged from 0.4 to 14.0 %. Vertical swell (i.e. perpendicular to bedding) was found to always exceed horizontal swell in the 3D cube test, by up to 4 times. This swell anisotropy was greatest for the Knoll Manor 2 and Whitecliff Bay 1 samples. Maximum swell was typically achieved between 10 and 100 hours from start of test. Free swell test data had a range of 18 to 80 %. No correlations were obtained between free swell, volumetric swell strain, and the index parameters liquid limit, plasticity index, liquidity index, and activity. This was also found to be the case for the Mercia Mudstone (Hobbs et al., 1998).

The Building Research Establishment (BRE) Digest 240 (BRE, 1993) gave a scale of susceptibility to volume change (i.e. swelling or shrinkage) for over-consolidated clays in terms of a modified plasticity index, Ip'.

Volume change susceptibility:

I_p'	Volume change potential
>60	very high
40–60	high
20–40	medium
<20	low

where Ip' is a modified plasticity index:

$$I_p' = I_p \frac{\% <0.425mm}{100\%}$$

The purpose of the modified plasticity index is to take account of the proportion of fines in relation to the total sample and to reduce the measured plasticity index in proportion. Many Atterberg limit data do not include <0.425mm results. This may be because the sample did not require sieving, or that a small number of coarse particles were removed by hand, without sieving. The modified plasticity index, I_p' and volume change susceptibility data for the principal members are shown.

Table 1 Volume change susceptibility for the Lambeth Group.

Formation	Median I_p' (%)	Volume change susceptibility
Reading Formation, upper mottled clays (RBUMCL)	28.0	Medium
Reading Formation, undifferentiated mottled clays (RBMCL)	33.0	Medium
Reading Formation, lower mottled clays (RBMCL)	28.0	Medium
Upnor Glauconitic Sands (UPRGS)	17.7	Low
Woolwich Formation, laminated beds (WLLB)	23.4	Medium
Woolwich Formation, laminated shelly clays (WLLSC)	29.8	Medium

The BRE Digest 240 (BRE, 1993) classification did not indicate the actual volumetric shrinkage to be expected for each of the volume change potential categories. Net volume changes depend on the initial saturation condition of the test sample. In the case of the shrinkage limit test this is usually natural moisture content, whereas in the case of the linear shrinkage test it is close to the liquid limit. All the Reading Formation Mottled Clay samples tested at BGS for shrink/swell gave a 'medium' volumetric susceptibility classification obtained by the BRE method (Table 1).

1 Introduction

This is the concluding interpretative report on the shrinkage and swelling properties of mudstones and clays of the Lambeth Group. It forms the third stage of the project entitled 'The shrinkage and swelling behaviour of UK clay soils'; the previous two stages being the 'Gault (Clay) Formation' (Jones and Hobbs, 1998a) and 'mudstones of the Mercia Mudstone Group' (Jones and Hobbs, 1998b). The current report is based on data presented in a factual report (Jones, 2001). The aim of this project is to determine the shrinkage and swelling properties of UK mudrocks and clays and to investigate the relationships between these properties, both across and within the formations. This report is concerned principally with the clay-rich strata within the Reading and Woolwich formations of the Lambeth Group and is based on ten samples obtained from seven sites across southern England (Figure 1). This work is complementary to the project entitled 'The engineering geology of UK rocks and soils' for which there is a British Geological Survey (BGS) report on the Lambeth Group in preparation.

The work described in this report deals with clays and mudstones of the Reading and Woolwich formations of the Lambeth Group. The Lambeth Group forms part of a Palaeogene (Tertiary) sedimentary sequence laid down across south-east England 58 to 59 million years ago (Hight et al., 2000). The depositional environment was one of shallow-marine, lagoon, and barrier-beach in a sub-tropical climate. Rapid sea-level changes resulted in the wide lithological variability characteristic of the Lambeth Group strata. Gentle folding of the Lambeth Group strata took place in Miocene times, some 20 million years ago, when the London and Hampshire Basins of today were formed. More recently, periglaciation caused considerable disruption to the Lambeth Group strata in the near surface. The stratigraphic sequence is summarised in Table 2.

Both undisturbed and disturbed samples of weathered and unweathered material were tested using a variety of methods, most of which followed internationally recognised British or American standard procedures. Two shrinkage limit determinations, using test equipment developed at BGS, were included. These tests were non standard but sought to measure the same parameters as the standard tests. Inherent in the project is a commitment to examine ways of improving existing direct test methods. An example of this is the development of a new test method for the determination of shrinkage limit, 'SHRINKIT'. This has been developed to improve accuracy, widen applicability, and to eliminate the use of mercury on health and safety grounds.

The test methods used in the work reported here can be grouped into four categories:

a) direct swelling tests
b) direct shrinkage tests
c) index tests
d) consolidation tests

The purpose of the index tests was to classify the soils and to investigate correlations between index properties and direct swelling and shrinkage test results. Consolidation tests were carried out in a conventional oedometer. In

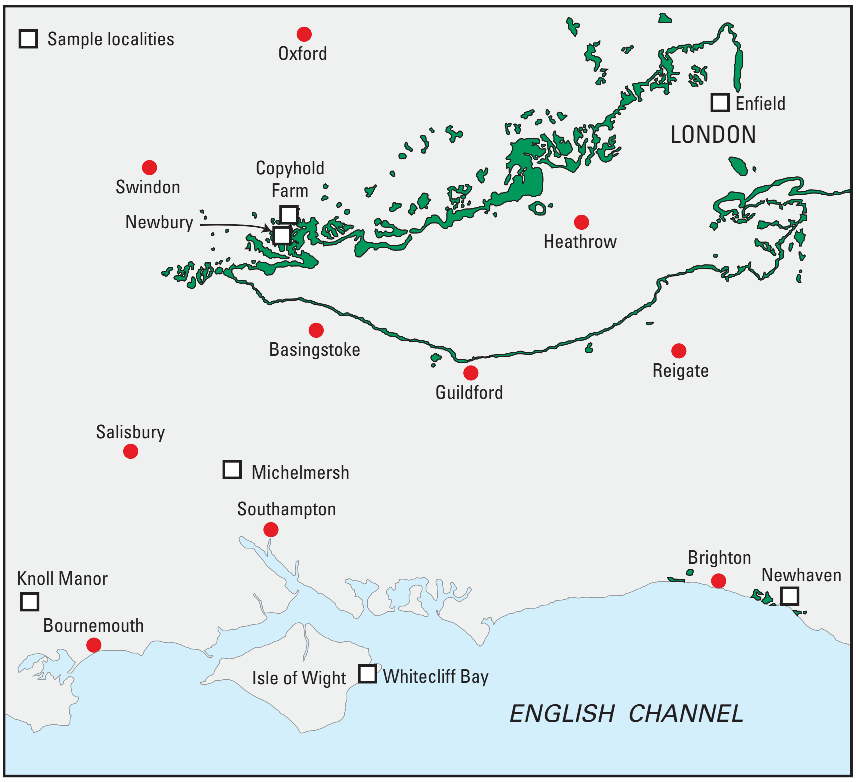

Figure 1 Map showing the Lambeth Group outcrop and sampling locations.

Table 2 Summary stratigraphic sequence (after Hight et al., 2000).

Formation	Previous usage	Units
Reading Formation	Reading Beds	**Upper Mottled Clay (RBUMCL)**
		Lower Mottled Clay (RBLMCL)
		'ferruginous sand'
		'lower mottled sand'
Woolwich Formation	Woolwich Beds	Upper Shelly Clay
		Laminated Beds (WLLB)
		'striped loams'
		Lower Shelly Clay (WLLSC)
Upnor Formation	Bottom Bed	**Glauconitic Sand (UPRGS)** 'pebble bed' (at top)
	Basement Beds (of Reading Beds)	

(Units in **capitals** represented in this study)

addition to the test results reported here, mineralogical, geochemical, and scanning electron microscopy studies have been carried out.

Test samples consisted of hand-prepared, undisturbed block samples, undisturbed core tube samples, and disturbed bag samples, all obtained in the field from shallow hand-dug pits at both coastal and inland sites.

A brief assessment of all swell/shrink project test data produced to date has been made, including Gault Formation and Mercia Mudstone Group data, in order to identify possible multivariate correlations between parameters. If valid, these may then be applied to the Lambeth Group sample test data.

2 Significance of shrinkage and swelling

Many conurbations, transport routes, services, and structures are founded on clay-rich soils and rocks in Britain. Typically, these consist of alluvial, glacial, and weathered bedrock formations. The clays within these are widespread and the materials constitute a familiar hazard to engineering construction in terms of their ability to swell or shrink (that is, volume change resulting from a change in effective stress) usually caused by seasonal changes in water content. Superimposed on these widespread climatic influences are local ones such as tree roots and leakage from water supply pipes and drains. Removal or severe pruning of trees results in swelling problems, as the desiccated soil rehydrates. The swelling of clay soils after trees have been removed can produce either very large uplifts or very large pressures (if confined), over a period of many years (Cheney, 1986).

Swelling and shrinkage are not fully reversible processes (Holtz and Kovacs, 1981). The process of shrinkage causes cracks, which on rewetting, do not close perfectly, and hence cause the soil to bulk-out and also allow enhanced access to water. Shrinkage cracks may become infilled with other material from the ground surface, thus imparting heterogeneity to the soil. When material falls into cracks the soil is unable to move back causing enhanced swelling pressures.

Whilst much investigation has been carried out worldwide to infer shrinkage and swelling behaviour from soil index properties such as plasticity, few direct data are available in UK geotechnical databases. This is partly due to the fact that index test standards are more explicit and accepted worldwide, and partly that direct swelling and shrinkage tests are often difficult to perform, particularly on undisturbed samples. Index tests, such as liquid and plastic limits, require complete remoulding of the material. This results in the breaking down of the soil structure and much of the fabric. However, direct shrinkage and swelling tests may be carried out on either undisturbed or remoulded samples.

Shrinkage and swelling are two essential aspects of the relationship between volume change and water content of clay soils. However, despite the proliferation of test methods for determining these two properties by direct measurement, they are rarely employed in the course of routine site investigations in Britain. The reason for the lack of direct shrink/swell test data is that few engineering applications have a perceived requirement for these data for planning, design or construction even though problems may be averted or anticipated by examining direct shrink/swell properties at the early stages of a project. This means that few data are available for assessing the nature and variation in shrink/swell behaviour of the major clay formations, and reliance has to be placed on estimates based on index parameters, such as liquid limit, plasticity index, and density (Reeve et al., 1980; Holtz and Kovacs, 1981; Oloo et al., 1987). Such empirical correlations may be based on a small data set, using a specific test method, and for samples from only a small number of sites. Index data alone may be insufficient to characterise the volume change properties of many British soils, including the clay-rich units of the Lambeth Group.

Frequently, those buildings and structures most affected by shrink/swell, e.g. houses, pipelines, pylons, pavement, and shallow services, receive a cursory site investigation, if any. Such site investigations tend to focus solely on plasticity, consistency, and possibly strength and consolidation. It is usually not until some time after construction that problems associated with swelling and shrinkage become known, and remedial measures are required. Swelling and shrinkage behaviour may also be predicted by reference to clay mineralogy, or to physico-chemical composition factors such as surface area or intra-plate distance. These relationships may ultimately give better correlations with actual behaviour than the use of index properties (Hobbs et al., 1982). However, such relationships are more difficult to determine and outside the experience of many contractors and laboratories.

3 Sampling

3.1 SAMPLING METHODS

The initial stage of this investigation set out to examine the swelling and shrinkage properties of the principal clay-rich units of the Lambeth Group taken from seven sites in southern England. At all the locations 250 x 100 mm diameter core tubes and 250 x 250 x 100 mm block samples were taken from pits, which were hand dug to a mean depth of about 0.5 m into slopes of between 10 and 30^{o}. In addition, disturbed samples of in situ material were collected in bags. The core tube and block samples were prepared by first forming a cuboid pedestal in the base of the pit, and then, by a combination of pushing the sharpened steel cutter tube on to it while trimming the clay beneath it, until the tube was filled. It was released by cutting away the clay below the tube. Top and bottom surfaces of the sample were trimmed and sealed with cling-film, foil, and tape. Figures 2 and 3 show the tube sampling equipment used to obtain 'undisturbed' samples. The core tube (and block samples) were oriented vertically in each case.

3.2 SAMPLING SITES

Samples were collected from seven sample sites (Figure 1).

3.2.1 Newbury by-pass, Berkshire

The Newbury by-pass was built by a partnership of Highways Agency, Costain Civil Engineering and the Mott MacDonald Group during 1998 and 1999. It rerouted the north–south A34 trunk road away from the town centre and to the west. The three sampling sites were relatively close together, situated approximately 3 km north-west of Newbury. The samples were collected during construction of the road and excavation of a major road cut in the central section of the by-pass near Redding Farm. At the sampling site the Lambeth Group comprised an inter-bedded sequence of clays and sands of the Reading and Woolwich facies respectively. The clays are locally cut by channel deposited sands. The sampling sites were located at SU 458 697, at an elevation of 112–118 m above OD. Samples were taken from fresh, unweathered material; surface disturbance was considered to be negligible.

3.2.2 Copyhold Farm, Berkshire

The Copyhold Farm quarry site is owned by Tarmac but is no longer active. The quarry is situated about 6 km north of Newbury, 1 km east of Junction 13 of the A34, and was formerly a sand pit. Approximately 4.5 m thickness of Reading facies clays were exposed on the west face of the pit, overlying fine-grained cross-bedded Woolwich sands. The sampling site was located at SU 491 729, at an elevation of 100 m above OD. The samples were taken from the west face of the pit. Access to the sampling site was good due to the proximity of the pit to the haul road.

3.2.3 Newhaven, Sussex

The Newhaven site, a natural sea cliff, is overseen by the East Sussex County Council. The cliff face is situated about 1.5 km south of the centre of Newhaven, on the south coast. The strata of the Lambeth Group crop out approximately two-thirds of the way up the cliff, being underlain by Upper Chalk. The sequence comprises a basal flint conglomerate approximately 0.5 m thick, overlain by 1.5 m of sand. This was succeeded by a variable clay sequence up to 6 m in thickness. The clays vary from pale to dark grey and contain variable amounts of crystalline gypsum (selenite) and, locally, beds rich in comminuted shells. The sequence is overlain by London Clay. The sampling site was located at TQ 444 000 at an elevation of 25 m above OD. Access to the section was via a natural low angle gully in the cliff.

3.2.4 Whitecliff Bay, Isle of Wight

The Whitecliff Bay site, a natural sea cliff, is overseen by English Nature. The cliff face is situated about 3 km south-east of Brading, 7.5 km south of Ryde, on the east coast of the Isle of Wight. The site is on the north side of the Isle of Wight monocline and the strata are vertical. The Lambeth Group is bounded by Upper Chalk and London Clay. There is no arenaceous material within the sequence and the

Figure 2 'Undisturbed' tube sampling equipment.

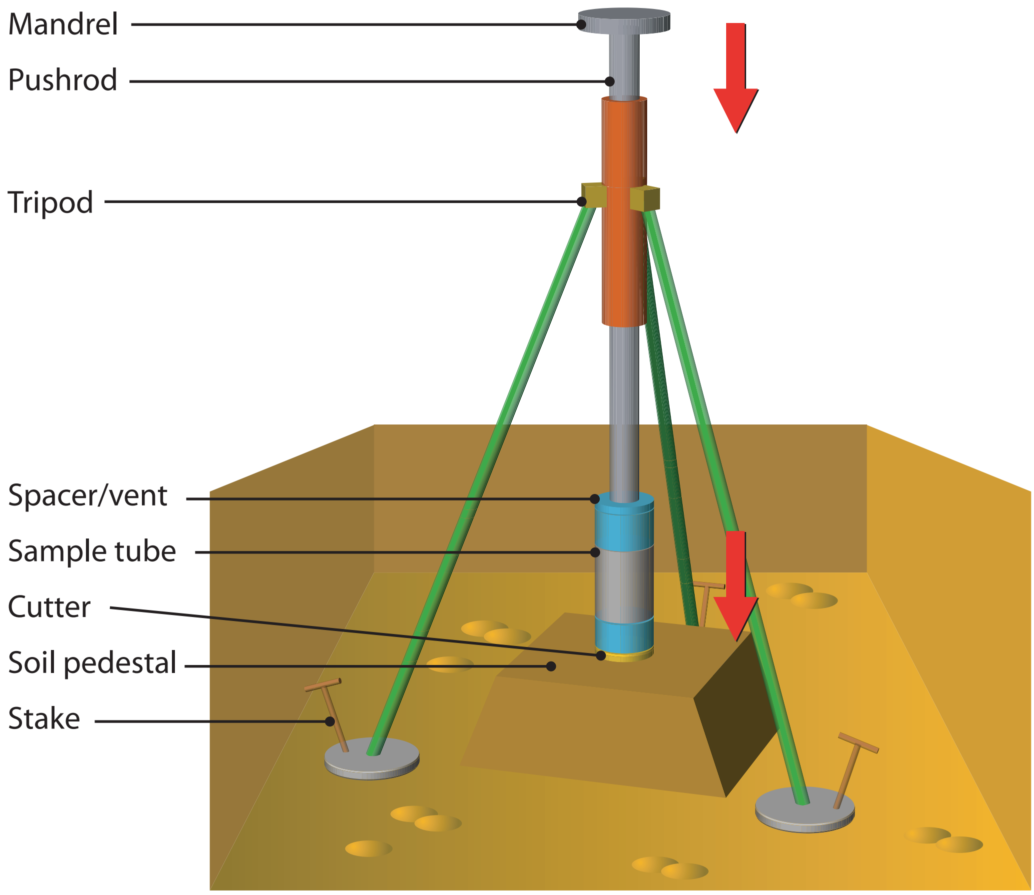

Figure 3 Diagram of 'undisturbed' tube sampling equipment.

whole can be assigned to the Reading facies. The clays vary from very pale grey to cherry red. The sampling site was located at SZ 638 856 at an elevation of 1 m above OD. Access to the section was via the beach, and, owing to severe slumping of the Reading Beds, samples had to be taken at beach level from in situ material.

3.2.5 Michelmersh, Hampshire

The Michelmersh Brick Pit site is owned and operated by Michelmersh Brick Co. Ltd. The quarry is situated about 0.5 km west of Michelmersh, 5 km north of Romsey. The site is used for the extraction of clay for making bricks. The site had been severely disrupted following digging out by the operators, leaving only the south face of the pit in an undisturbed state. This was a near-vertical bank rising from the haul road, about 2.5 m high and partially covered in vegetation. At the top of the bank about 0.75 m of flinty clay head deposits were present. The Lambeth Group was partially replaced by a fossiliferous London Clay channel deposit (London Clay age confirmed by marine fauna present). The clays varied in colour from dark grey, through grey/red mottled to pale grey. The sampling site was located at SU 345 259 at an elevation of 50 m above OD. Access is reasonably good in dry weather, but the haul roads were partly flooded at the time of sampling.

3.2.6 Knoll Manor, Dorset

The Knoll Manor Brick Pit site is owned by Pilkingtons Tiles Ltd. and operated by Oasis (excavation contractors). The pit is situated about 0.75 km north of Corfe Mullen, 4.75 km south-west of Wimborne Minster. The site is used for the extraction of clay for making bricks and tiles. Although the clays resemble the mottled Reading Clays of elsewhere, they have been assigned (stratigraphically) to the West Park Farm member of the London Clay. There is some debate as to whether this deposit is of basal London Clay or Lambeth Group age; being underlain by Chalk and overlain by deposits characteristic of the lowest members of the London Clay elsewhere. At the pit the sequence comprised an uppermost red-grey mottled clay (Site 1) with a lower red clay (Site 2). The uppermost clay was overlain by a thin (0.25 m) sandy glauconitic flint conglomerate (elsewhere taken as the base of the London Clay) succeeded by fine-grained poorly consolidated sandstone. Site 1 was located about 10 m above Site 2 and approximately 1.5 m below the conglomerate; Site 2 was at the lowest accessible point in the pit. The sampling sites were located at SY 3973 0975, at elevations of 30 m and 20 m above OD. Access to the sampling site was reasonably good, except where the haul roads were blocked with debris.

3.2.7 Enfield

The Enfield Borehole site was drilled by Oakley Soils & Concrete Engineering Ltd. The borehole is situated about 1.5 km south of Enfield town centre. The borehole was drilled to a depth of 10 m below ground level. The borehole log provided by the engineers showed made ground to 1.4 m and Reading Clay in the remainder of the borehole. Bulk and U100 core tube samples were available. Testing was carried out on a core tube sample at a depth of 6.5 m below ground level, 20 m above OD, which was described as 'very stiff closely fissured brick red, grey, yellow/brown mottled silty slightly sandy CLAY' in the borehole log. The borehole site was located at TQ 321 954, with ground level at an elevation of 26.5 m above OD.

3.3 SAMPLE DESCRIPTIONS

The size of the block samples and tube samples were 300 x 300 x 150 mm and 300 x 100 mm (diameter), respectively. Colours were described using Munsell Soil Color Charts (Macbeth, 1988).

Sample: Newbury (NB1), Reading Formation (lower)
Colour: 5Y 6/1 Light Grey / Grey with mottling 10R 4/8 Red, 10YR 6/8 Brownish Yellow and 2.5YR 3/4 Dark Reddish Brown
Consistency: Stiff
Discontinuities: Fissured. Slakes very slightly. No effervescence in 25% HCl
Soil type: CLAY of intermediate plasticity (CI) with random limonitic accumulations up to coarse sand-sized particles, and a slightly waxy texture

Sample: Newbury (NB2), Reading Formation (lower)
Colour: 5Y 5/2 Light Olive Grey with some mottling of 10R 4/8 Red
Consistency: Firm
Discontinuities: Coated fissures. Slakes slightly in water. No effervescence in 25% HCl
Soil type: Slightly silty CLAY of high plasticity (CH)

Sample: Newbury (NB3), Reading Formation (lower)
Colour: 10YR 5/3 Brown with some minor mottling of 10YR 6/1 Light Grey / Grey and bands of 10YR 5/8 Yellowish Brown
Consistency: Firm
Discontinuities: Fissured. Slakes very slightly in water. No effervescence in 25 % HCl
Soil type: Slightly silty CLAY of intermediate plasticity (CI) with bands of sand-sized ferruginous (limonitic) concretions

Sample: Copyhold Farm (CF1), Reading Formation
Colour: 5Y6/1 Light Grey / Grey highly mottled with 10R 4/8 Red, 10YR 6/8 Brownish Yellow and 2.5 YR 3/4 Dark Reddish Brown
Consistency: Soft
Discontinuities: Very fissured. Slakes in water. No effervescence in 25 % HCl
Soil type: Silty CLAY of intermediate to high plasticity (CI/CH) with numerous ferruginous (limonitic) concretions

Sample: Newhaven (NH1), Woolwich Formation (lower)
Colour: 10YR 3/1 Very Dark Grey with slight mottling of 10YR 6/6 Brownish Yellow and some weathering grade II material of 5Y 4/3 Olive
Consistency: Stiff
Discontinuities: Slightly fissured. Slakes very slightly in water. Moderate effervescence in 25% HCl. Contains shell fragments
Soil type: Sulphurous silty CLAY of high plasticity (CH) with rare calcareous shell fragments and occasional crystalline gypsum (selenite)

Sample: Whitecliff Bay (WB1), Reading Formation (upper)
Colour: 5Y 5/1 Grey with slight mottling of 2.5YR 4/4 Reddish Brown
Consistency: Firm, crumbly (variable with fissuring)
Discontinuities: Highly fissured. Slakes slightly in water. No effervescence in 25 % HCl
Soil type: CLAY of intermediate plasticity (CI) with ferruginous (limonitic) concretions

Sample: Michelmersh (MM1), Reading Formation
Colour: 5Y 6/1 Light Grey / Grey with mottling of 2.5 YR 4/4 Reddish Brown, 5Y 6/4 Pale Olive and 10YR 6/8 Brownish Yellow
Consistency: Firm
Discontinuities: Fissured. No slaking in water. No effervescence in 25 % HCl
Soil type: CLAY of intermediate plasticity (CI) with ferruginous (limonitic) concretions

Sample: Knoll Manor (KM1), Reading Formation
Colour: 10YR 4/1 Dark Grey with heavy mottling of 10R 3/6 Dark Red, 10R 3/2 Dusky Red and some weathering Grade II material of 2.5Y 4/4 Olive Brown
Consistency: Very Stiff
Discontinuities: Fissured. No slaking in water. No effervescence in 25 % HCl
Soil type: Sulphurous CLAY of intermediate plasticity (CI) with ferruginous limonitic concretions

Sample: Knoll Manor (KM2), Reading Formation
Colour: 2.5YR 4/6 Red with mottling of 7.5YR 4/6 Strong Brown and 5Y 5/1 Grey
Consistency: Firm
Discontinuities: Slightly fissured. No slaking in water. No effervescence in 25 % HCl
Soil type: Slightly silty CLAY of intermediate plasticity (CI) with very finely disseminated ferruginous (limonitic) concretions

Sample: Enfield (EN1), Reading Formation
Colour: 10YR 4/4 Dark Yellowish Brown with moderate mottling of 5Y 5/2 Olive Grey and 2.5YR 4/4 Reddish Brown
Consistency: Stiff
Discontinuities: Moderately fissured. No slaking in water. Slight effervescence in 25 % HCl.
Soil type: Sandy silty CLAY of high plasticity

The mineralogical properties of the samples have been obtained from X-ray diffraction (XRD) analysis for the bulk samples and for the fraction smaller than 2 mm. These include major, minor, and trace constituents, and determinations of specific surface area (SSA). The results are summarised in Table 3.

Table 3 Summary of mineralogical results (after Pearce at al., 1993).

Sample No.	Sample site	Grid ref.	Formation	Description	Bulk XRD			XRD results for (<2 mm) fractions			SSA
					Major	*Minor*	*Trace*	*Major*	*Minor*	*Trace*	*(M^2/g)*
NB1	Newbury	SU458697	Lower Reading	Pale grey with reddened streaks, stiff clay	Quartz	Smectite kaolinite mica K-feldspar	Albite	Smectite	Kaolinite illite		198
NB2	Newbury	SU458697	Lower Reading	Pale grey, firm clay with some Fe-stained horizons	Quartz	Smectite mica K-feldspar	Kaolinite	Smectite	Kaolinite illite		160
NB3	Newbury	SU458697	Lower Reading		Quartz	Mica	Kaolinite K-feldspar	Smectite illite	Kaolinite		175
CF1	Copyhold Farm	SU491729	Reading	Pale−med.grey, soft clay, w some rusty staining admixed with m.sand	Quartz	Smectite kaolinite mica K-feldspar Albite	Hematite	Smectite	Kaolinite illite		137
NH1	Newhaven	TQ438856	Lower Woolwich	Dark brown, malleable silty clay containing some roots	Quartz	Smectite kaolinite mica halite pyrite	K-feldspar albite	Smectite	Kaolinite illite	Goethite	175
WB1	Whitecliffe Bay	SZ438856	Upper Reading	Medium grey soft clay with sparse red, Fe-rich spots	Quartz	kaolinite, mica	Smectite K-feldspar albite hematite	Kaolinite,	Smectite illite		175
MM1	Michelmersh	SU345259	Reading	Pale grey, malleableclay with abundant red, Fe-rich patches	Quartz	Smectite kaolinite mica	K-feldspar albite hematite goethite	Smectite	Kaolinite illite		167
KM1	Knoll Manor	SU974978	Reading	Medium grey /buff clay with red, Fe-rich spots	Quartz	Kaolinite mica halite	K-feldspar albite hematite	Kaolinite	Smectite, illite	Goethite	137
KM2	Knoll Manor	SU974978	Reading	Medium red /brown, friable silty clay	Quartz	Kaolinite mica	K-feldspar albite hematite goethite	Kaolinite	Illite	Smectite goethite	68
EN1	Enfield	TQ321954	Reading	Dry, hard pale grey/buff clay, with some rusty staining	Quartz		Kaolinite mica K-feldspar albite	Smectite	Kaolinite illite	Goethite	175

4 Methods

4.1 GENERAL

The methods used by research laboratories to test clay-rich material described in the literature tend to follow broadly two separate routes for **clays** and for **mudrocks**; the former tending to occupy the civil engineering industry and the latter the oil and mining industries. Considerable research work has been carried out on behalf of the oil and mining industries, especially in the USA, on the swelling behaviour of 'compact' clays and mudrocks, in particular clay shales. In the engineering industry swelling pressure causing damage in tunnels has been reported by Madsen (1979). However, this is not usually the case, albeit at greater depths, in the mining industry. Workers in arid environments, such as the southern USA, Australia, and southern Africa, have produced data on swelling and its effect on foundations (Donald, 1970; O'Neill and Poormoayed, 1980; Madsen and Muller-Vonmoos, 1985; Sarman et al., 1994). In the oil industry, the swelling of shales and 'compact' clays in borehole and well linings has been a topic of interest. The laboratory test methods developed differ considerably from those applied by the civil engineering industry, and tend to duplicate the particular phenomenon causing problems. For example, the moisture activity index test (Huang et al., 1986) duplicates changes in relative humidity in the air passing through mine tunnels, and consequent swelling of the tunnel lining. However, the confined swelling pressure test is relatively universal. Work has been done by the former Soil Survey and agricultural organisations because shrinkage affects the near-surface in Britain. Reeve et al. (1980) described the determination of shrinkage potential for a variety of soils classified on a pedological basis.

There are numerous methods of testing for the shrinkage and swelling properties of clay soils. Of these, some are more relevant to this programme of testing than others. These methods were discussed in greater detail by Hobbs and Jones (1995), the positive and negative points of each method were considered and the reasons for the selection and rejection of methods for the project testing programme presented.

Swelling tests may be broadly divided into those tests that attempt to measure the deformation or strain resulting from swelling, and those which attempt to measure the stress, or pressure, required to prevent deformation due to swelling. These two types are referred to here as swelling strain and swelling pressure tests, respectively. Swelling strain tests may be linear i.e. one dimensional (1D) or volumetric, i.e. three-dimensional (3D). Swelling pressure tests are usually one-dimensional. The surcharge applied may be constant or, as in the BGS-developed test, dynamically reactive. Shrinkage tests deal solely with the measurement of shrinkage strain in either 1D or 3D. The 1D swelling pressure test developed at BGS is based on a design described in Donald (1970).

4.2 SELECTED METHODS

The following are those tests carried out by the authors in the geotechnical laboratories of BGS:

- determination of moisture content (BS1377:1990; Part 2, Test 3.2) (BSI, 1990)
- determination of the liquid limit (BS1377:1990; Part 2, Test 4.3 and grease-worker option) (BSI, 1990)
- determination of the plastic limit and plasticity index (BS1377:1990; Part 2, Test 5 & 5.4) (BSI, 1990)
- determination of density (BS1377:1990; Part 2, Test 7.2) (BSI, 1990)
- determination of particle density (BS1377:1990; Part 2, Test 8.3) (BSI, 1990)
- determination of particle size distribution (BS1377:1990; Part 2, Test 9.2 & 9.5) (BSI, 1990)
- linear shrinkage (BS1377:1990; Part 2, Test 6.5) (BSI, 1990)
- volumetric shrinkage (BS1377:1990; Part 2, Test 6.3) (BSI, 1990)
- free swell (Holtz and Gibbs, 1956, and Head, 1992, Volume 1, Section 2.8.3)
- three-dimensional swelling strain (ISRM, 1981, Part 2, Test 3)
- one-dimensional swelling strain (ASTM, 1995, Section 4 Construction, Test D 4546)
- one-dimensional swelling pressure (Hobbs et. al. 1982, Section 6.3)
- one-dimensional consolidation properties (BS1377:1990; Part 5, Test 3) (BSI, 1990)
- determination of the K_0 swelling in a triaxial cell (Menzies et. al., 1977)

The following are those tests carried out in the mineralogical laboratories of BGS:

- X-ray diffraction analysis (BGS)
- X-ray fluorescence analysis (BGS)
- other geochemical analysis (BGS)
- scanning electron microscope (BGS)

4.3 REJECTED METHODS

The following tests are those considered unsuitable, or impractical (see Hobbs and Jones, [1995] for reasons):

- determination of density by immersion in water (BS1377: Part 2: 1990: 7.3) (BSI, 1990)
- pressure plate-consolidometer (Obermeier, 1974)
- osmotic cell-consolidometer (Obermeier, 1974)
- humidity test (Huang et al., 1986)
- swell potential by radio-frequency dielectric dispersion (Basu and Arulanandan, 1974)
- triaxial swelling test (Yesil et al., 1993)
- tensiometer probe method of suction measurement (Ridley and Burland, 1993)
- filter paper method of suction measurement (Chandler and Gutierrez, 1986)
- chemical tests (BS1377: Part 3: 1990) (BSI, 1990)

5 Results and analysis

5.1 INDEX DATA

Table 3 shows the index test results, along with swelling and shrinkage data, for the samples collected at the seven sites listed in Tables 1 and 2. Natural water contents ranged from 17.5 to 24.6 %. Liquid limits ranged from 45 to 64 % and plastic limits from 18 to 28 %. Plasticity indexes ranged from 23 to 36 % and liquidity indexes from –0.31 to +0.15; the majority being less than unity.

Index test data are shown as a Casagrande plasticity chart in Figure 4. This shows that the plasticities of the samples are closely grouped, and fall within the 'intermediate' to 'high' plasticity categories. Plasticity index, I_P is frequently used as an indicator of likely shrink/swell behaviour, and is defined as follows:

$$I_P = w_L – w_p \quad \% \qquad \text{--1}$$

(where: w_L & w_P are the Atterberg limits: liquid limit and plastic limit)

Activity data are shown on a plot (Figure 5) proposed by Skempton (1953) and adapted to give classifications of expansive potential by Williams and Donaldson (1980) and Taylor and Smith (1986).
Skempton (1953) defined activity, A_c, as follows:

$$A_c = \frac{I_P}{\%Clay} \qquad \text{--2}$$

(where: I_p is the plasticity index; %Clay is the particle-size fraction <0.002 mm)

This ratio is designed to give an indication of the relative contribution of the plasticity of the clay minerals to the soil's behaviour. Activities ranged from 0.48 to 0.93. The plot (Figure 5) shows that all the samples tested fell within the 'inactive' to 'normal' activity classes, and the 'high' expansive potential class.

5.2 SWELLING RESULTS

Results of the swelling tests, for the samples collected at the seven sites listed in Tables 1 and 2, are reported in Jones (2001) and given along with shrinkage and index data in Table 3. Correlations between swelling parameters, and between swelling and index parameters, were examined. The spreadsheet correlation matrix (Table 4) was useful in this respect.

Four types of direct swelling test were carried out on the Lambeth Group samples. These were: 1D swelling pressure (Hobbs et al., 1982), 1D swelling strain (Anon, 1990), 3D swelling strain (Anon, 1981), and free-swell (Holtz and Gibbs, 1956). Of these, only the free-swell test was carried out on a 'disturbed' specimen. The remainder were carried out on 'undisturbed' specimens obtained from block or tube samples taken in the field.

5.2.1 The one-dimensional (laterally confined disc) swelling pressure test (Hobbs et al., 1982)

Peak swelling pressures ranged from 16 to 91 kPa, with a mean of 26 kPa and a median of 21.7 kPa.

No significant correlations were found for the Lambeth Group between swelling pressure, P_{sw} and index parameters, either individually or combined. This is probably due to the fact that swelling pressure is influenced by stress history and sampling disturbance.

A good positive correlation was found between swelling pressure, P_{sw} and 1D swelling strain, e_{1D} (Figure 6) as follows:

$$P_{sw} = 10.4\,(\varepsilon_{1D}) – 19.6 \quad (r^2 = 0.92, n{=}8) \text{ --3}$$

These two tests were carried out on separate specimens from the same sample, with the same dimensions.

Sarman et al. (1994) proposed the following relationship between swelling pressure, P_{sw} (kPa) and volumetric swelling strain, DV (%) for a variety of US mudrocks:

$$P_{sw} = 400 - 100\,(\Delta V) \qquad \text{--4}$$

The equivalent relationship for the Lambeth Group has a poor correlation ($r^2 = 0.55$) and swelling pressures are about 35 times less.

There are no further significant correlations between swelling pressure and other parameters. Very small swelling strains greatly reduce measured swelling pressure. This may occur within fissure voids (Abduljauwad et al., 1998). The stress history and starting conditions of the test sample play an important part in determining the swelling pressure result; e.g. depth of burial, degree of over-consolidation, moisture content, degree of sample disturbance. However, the good correlation between swelling pressure and 1D swell strain suggests that the sample preparation for these two tests has been of comparable quality.

A good relationship was described for deeply buried Jurassic mudrocks from Switzerland between measured swelling pressure and swelling pressure determined from theoretical clay particle spacing (Madsen, 1979). There is no correlation between swelling pressure and surface area for the tests reported, though a good positive correlation is reported elsewhere for Mercia Mudstone. A multivariate relationship of swelling pressure with index data was reported for Israeli marls by Komornik and David (1969). This was of the following form:

$$P_{sw} = ae^{bP_x} \qquad \text{-- 5}$$

where: P_{sw} is measured swelling pressure (kPa)a, b are constants, $P_x = f\{\log_e (f\,\{w_L\} + f\,\{g_d\} – f\,\{w\}\}$, w_L is liquid limit (%), g_d is dry density (Mg/m^3), w is initial moisture content (%)

This relationship, and other similar relationships, did not produce a significant correlation when applied to the Lambeth Group clay samples.

The swelling pressure vs. time plots were rather irregular in most cases, due to the low values of swelling pressure in relation to the capacity of the apparatus, and the consequent loss of sensitivity. Swelling was observed to start at around the ten-minute mark in most cases. Peak

Table 4 Lambeth Group clay test data.

	INDEX										PARTICLE SIZE			SWELL					SHRINK			MIN	CONSOLIDATION		
														1D	1D	3D	3D		1D	3D	3D		C_s	C_c	P_c'
	w_o	γ_b	γ_d	γ_g	w_L	w_P	I_P	I_L	A_c	I_p'	CLAY	SILT	SAND	$P_{sw(1)}$	ε_{1D}	ε_{3D}	Δ_V	FS	LS	SL_{BS}	SL_{SK}	SSA			
	%	Mg/m^3	Mg/m^3	Mg/m^3	%	%	%			%	%	%	%	kPa	%	%	%	%	%	%	%	m^2/g			kPa
NB1	19.3	2.20	1.88	2.74	50	20	30	-0.04	0.93	29.6	32.1	63.8	4.1	90.9	10.5	5.0	14.0	25	14	10.4	8.1	155	0.060	0.184	283
NB2	21.8	2.05	1.67	2.70	57	24	33	-0.06	0.52	29.8	57.4	27.8	14.8	28.6	4.7	2.7	6.6	80	15	13.2		203	0.039	0.197	294
NB3	24.5	2.08	1.71	2.75	46	21	25	0.15	0.48	25.0	52.0	44.6	3.4	41.3	6.3	3.4	6.7	70	14	11.4			0.101	0.212	548
CF1	19.1	2.14	1.84	2.75	50	20	30	-0.04	0.57	30.0	52.3	46.8	0.9	32.2	6.0	3.8	7.1	53	16	9.2		185	0.026	0.160	820
NH1	24.6	1.92	1.49	2.93	64	28	36	-0.10	0.49	35.9	74.1	24.2	1.7	31.6	5.9	-	-	70	16	17.5		171	0.097	0.286	350
WB1	20.2	2.13	1.79	2.76	49	26	23	-0.25	0.61	22.8	37.4	55.9	6.7	17.2	3.0	0.3	0.4	80	15	9.9	12.3	172	0.050	0.180	272
MM1	18.2	2.03	1.66	2.80	45	21	24	-0.13	0.48	23.6	49.8	45.8	4.5	26.9	3.9	3.5	7.1	70	15	6.9		167	0.040	0.191	289
KM1	18.1	2.22	1.87	2.76	47	18	29	0.00	0.85	28.5	34.1	60.8	5.1	28.6	4.4	4.8	10.3	25	14	7.4		138	0.054	0.180	300
KM2	17.5	2.15	1.80	2.78	48	25	23	-0.31	0.51	23.0	44.7	53.0	2.3	16.2	3.5	4.7	7.6	18	12	15.0		69	0.044	0.171	286
EN1	20.5	2.17	1.82	2.74	54	20	34	0.03	0.67	34.0	50.7	22.2	27.1	75.7	8.0	-	-	63	16	12.7		216	0.063	0.228	500

Location Key:

NB	Newbury (Berks.)
CF	Copyhold Farm (Berks.)
NH	Newhaven (Sussex)
WB	Whitecliffe Bay (I.o.W.)
MM	Michelmersh (Hants.)
KM	Knowle Manor (Dorset)
EN	Enfield (Middx.)

Parameter key:

w_o	Water content (natural)
γ_b	* Bulk density
γ_d	* Dry density
γ_g	Particle density
w_L	Liquid limit
w_P	Plastic limit
I_P	Plasticity index
I_L	Liquidity index
A_c	Activity (Skempton)
I_p'	Modified plasticity index (BRE)
CLAY	Clay size fraction
SILT	Silt size fraction
SAND	Sand size fraction
$P_{sw(1)}$	* 1-D swelling pressure
ε_{1D}	* 1-D swelling strain
ε_{3D}	* 3-D swelling strain
Δ_V	Overall volume change
FS	Free swell
LS	Linear shrinkage
SL_{BS}	* Shrinkage limit (BS1377)
SL_{SK}	* Shrinkage limit (BGS - SHRINKIT)
C_s	* Swelling index (oedometer rebound)
C_c	* Compression index (oedometer)
P_c'	* Initial yield stress (oedometer)
SSA	Specific surface area (XRD)
*	undisturbed specimen

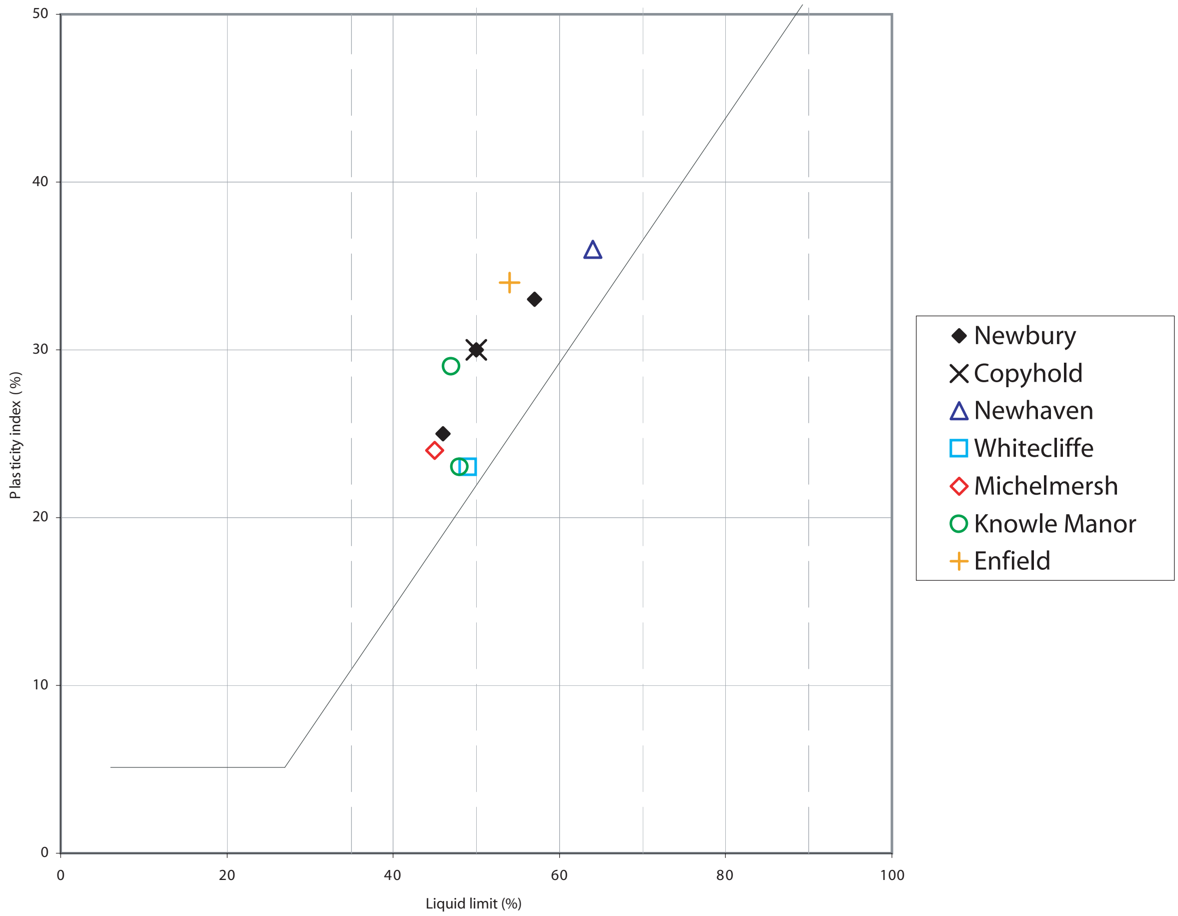

Figure 4 Casagrande plasticity plot (Lambeth Group clay).

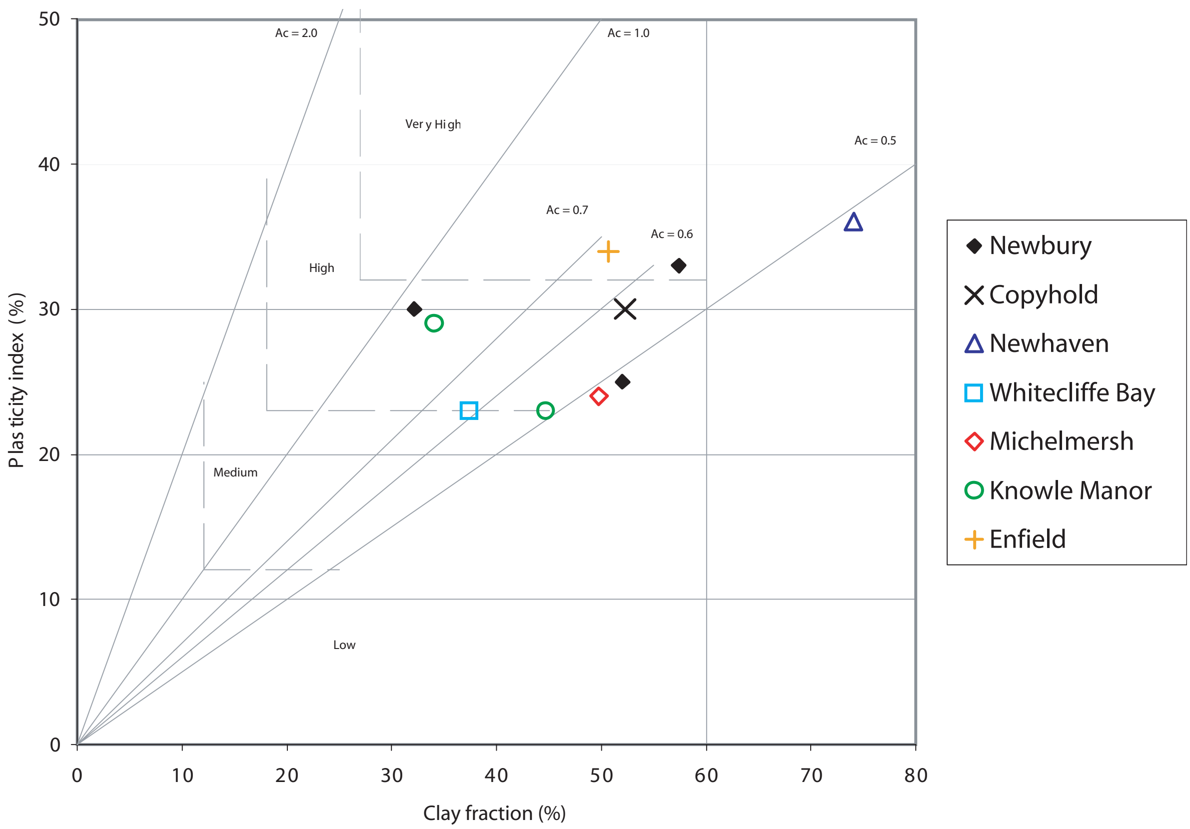

Figure 5 Skempton/Williams and Donaldson activity plot (Lambeth Group clay).

Table 5 Correlation matrix (Lambeth Group clays).

	w_o	γ_b	γ_d	γ_g	w_L	w_P	I_P	I_L	A_c	I_p'	CLAY	SILT	SAND	$P_{sw(1)}$	ε_{1D}	ε_{3D}	Δ_V	FS	LS	SL_{BS}	Δu	$SI_{(1)}$	$SI_{(2)}$	SSA	C_s
w_o	1																								
γ_b	-0.65	1																							
γ_d	-0.66	0.98	1																						
γ_g	0.34	-0.68	-0.70	1																					
w_L	0.58	-0.58	-0.60	0.48	1																				
w_P	0.41	-0.66	-0.67	0.56	0.58	1																			
I_P	0.43	-0.26	-0.28	0.22	0.83	0.03	1																		
I_L	0.47	0.05	0.06	-0.24	0.00	-0.61	0.41	1																	
A_c	-0.40	0.75	0.70	-0.33	-0.18	-0.55	0.16	0.19	1																
I_p'	0.42	-0.24	-0.25	0.31	0.80	0.01	0.98	0.41	0.18	1															
CLAY	0.68	-0.88	-0.85	0.58	0.72	0.53	0.53	0.12	-0.73	0.52	1														
SILT	-0.59	0.63	0.63	-0.26	-0.73	-0.34	-0.66	-0.23	0.54	-0.62	-0.84	1													
SAND	0.06	0.18	0.13	-0.41	0.24	-0.17	0.41	0.25	0.11	0.36	0.04	-0.57	1												
$P_{sw(1)}$	0.07	0.34	0.34	-0.24	0.09	-0.46	0.43	0.51	0.61	0.47	-0.22	-0.04	0.41	1											
e_{1D}	0.19	0.23	0.26	-0.13	0.19	-0.40	0.50	0.56	0.54	0.55	-0.08	-0.05	0.22	0.96	1										
e_{3D}	-0.36	0.42	0.39	0.12	-0.19	-0.64	0.28	0.27	0.38	0.39	-0.16	0.29	-0.41	0.44	0.48	1									
Δ_V	-0.25	0.47	0.43	-0.10	-0.03	-0.70	0.48	0.38	0.64	0.57	-0.32	0.35	-0.21	0.74	0.74	0.90	1								
FS	0.61	-0.65	-0.60	0.09	0.33	0.38	0.15	0.15	-0.60	0.09	0.55	-0.61	0.29	-0.22	-0.23	-0.81	-0.71	1							
LS	0.38	-0.40	-0.33	0.21	0.52	0.02	0.62	0.32	-0.13	0.63	0.50	-0.60	0.35	0.17	0.19	-0.46	-0.29	0.66	1						
SL_{BS}	0.54	-0.49	-0.53	0.46	0.76	0.72	0.44	-0.19	-0.38	0.44	0.64	-0.59	0.11	-0.01	0.09	0.04	-0.08	0.09	-0.02	1					
Δu	0.62	-0.26	-0.38	0.39	0.36	0.42	0.16	0.13	0.07	0.16	0.15	-0.05	-0.13	0.02	0.06	-0.05	0.07	0.02	-0.23	0.50	1				
$SI_{(1)}$	-0.19	-0.20	-0.17	0.11	-0.27	0.34	-0.56	-0.54	-0.22	-0.59	-0.18	0.35	-0.37	-0.59	-0.64	-0.80	-0.73	0.38	0.06	-0.41	-0.12	1			
$SI_{(2)}$	0.39	-0.44	-0.45	0.33	0.84	0.25	0.86	0.15	0.05	0.81	0.53	-0.58	0.27	0.14	0.21	-0.24	0.03	0.42	0.78	0.28	0.11	-0.05	1		
SSA	0.53	-0.24	-0.19	-0.18	0.41	-0.14	0.59	0.65	-0.04	0.54	0.34	-0.59	0.59	0.34	0.32	-0.48	-0.22	0.74	0.90	-0.10	-0.20	-0.05	0.74	1	
C_s	0.80	-0.39	-0.46	0.48	0.32	0.23	0.23	0.45	-0.11	0.30	0.37	-0.28	-0.06	0.23	0.30	0.04	0.10	0.18	0.04	0.46	0.81	-0.32	0.08	0.06	1

w_o	Water content (natural)
γ_b	* Bulk density
γ_d	* Dry density
γ_g	Particle density
w_L	Liquid limit
w_P	Plastic limit
I_P	Plasticity index
I_L	Liquidity index
A_c	Activity (Skempton)
I_p'	Modified plasticity index (BRE)
CLAY	Clay size fraction
SILT	Silt size fraction
SAND	Sand size fraction
$P_{sw(1)}$	* 1-D swelling pressure
ε_{1D}	* 1-D swelling strain
ε_{3D}	* 3-D swelling strain
Δ_V	Overall volume change
FS	Free swell
LS	Linear shrinkage
SL_{BS}	* Shrinkage limit (BS1377)
Δu	Percentage volume reduction/100g (BS1377)
$SI_{(1)}$	Shrinkage index (= w_p - SL)
$SI_{(2)}$	Shrinkage index (= w_L - SL)
SSA	Specific surface area (XRD)
C_s	* Swelling index (oedometer rebound)

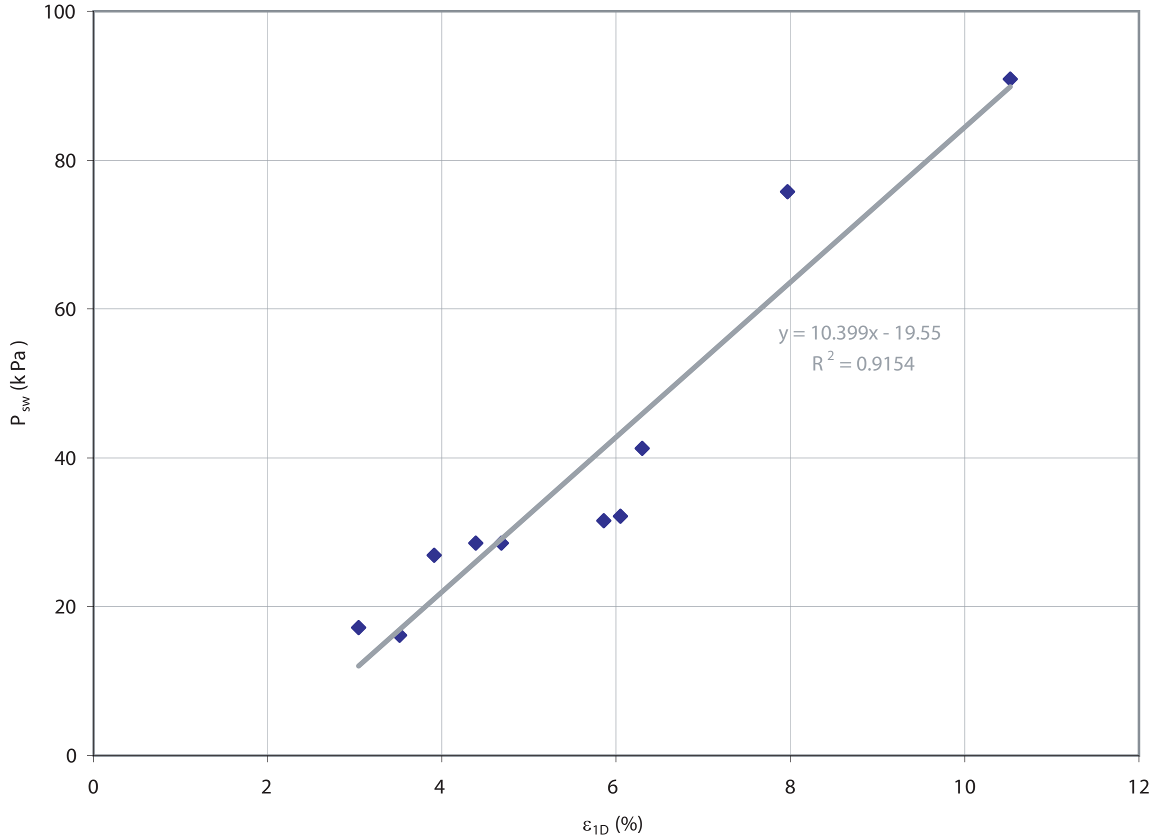

Figure 6 Plot of swelling pressure vs. 1D swelling strain (Lambeth Group clay).

swelling pressure was typically achieved between 40 and 100 hours from the start of the test, though samples WB1 and NB2 were slower. A decrease of pressure beyond the peak was noted in some cases, and was particularly marked in the case of sample CF1. With the possible exception of sample WB1, the test plots followed a sinusoidal curve, this being most marked for the higher-pressure samples. The least irregular curve was that for sample EN1.

5.2.2 The 1D (laterally confined disc) swelling strain test

The test was carried out so that swelling occurred perpendicular to bedding. The results ranged from 3.0 to 10.5 %. These results may be considered 'low' to 'moderate'. A good positive correlation was found between 1D swelling strain ε_{1D} and swelling pressure P_{sw} (refer to section 5.2.1 and Figure 6).

The 1D swelling strain test plots of swell strain vs. time show slight variability in shape, but were generally smooth and sinusoidal, typically having either a cessation, or a clear reduction of swelling rate, at around 15 hours elapsed time. There are no correlations of 1D swelling strain with any other parameters, with the exception of a poor correlation with 3D volumetric swell strain (r^2 = 0.74). Neither the 1D nor 3D swell strain test featured a surcharge load in the axis of swelling.

5.2.3 The 3D (50 mm unconfined cube) swelling strain test

A total of eight tests were carried out (samples NH1 and EN1 were not tested). The maximum (peak) swelling strain (perpendicular to bedding) ranged from 0.25 to 5.00 %, with NB1, KM1, and KM2 giving the highest values. Maximum volumetric strain ranged widely from 0.4 to 14.0 %. It was found that the swelling strain perpendicular to bedding was greater than in the other two orthogonal directions (parallel to bedding) in every case. This agrees with data for other mudrocks (Sarman et al., 1994; Bell et al., 1997). There does not appear to be a correlation between volumetric strain and clay mineralogy as might be expected. The two highest values were for samples NB1 and KM1, both having kaolinite, rather than smectite, as the major clay mineral.

The differences between perpendicular and parallel results, i.e. the amount of swell strain anisotropy, varied from sample to sample, being the greatest for KM2, and the least for NB1. Typically, the vertical component of swelling (i.e. perpendicular to bedding) was double that for the two orthogonal directions. There was no correlation between swell anisotropy and maximum volumetric strain as reported for the Gault Clay and Mercia Mudstone (Jones and Hobbs, 1998a; Jones and Hobbs, 1998b). Samples NB1 and KM1 showed the greatest overall volumetric strain. Swelling anisotropy tended to be maintained throughout the tests. Peak swelling strains were reached within a period of around six hours for samples NB2, NB3, CF1, and MM1 all of which showed remarkably similar plots. However, samples NB1, KM1, KM2, and WB1 differed in shape from the rest; sample WB1 having an irregular plot, and sample NB1 having a smooth plot with a very slow response peaking at around 200 hours. It is notable that sample NB1 has the highest 'activity' value.

The swelling anisotropy observed in all the samples is indicative of the anisotropic nature of the soil fabric. This is largely due to the preferentially oriented fabric of the Lambeth Group, i.e. the tendency for clay platelets to be aligned normal to an applied stress (overburden) and hence (parallel to bedding). This presents their 'active' face (largest surface area) in a vertical direction (normal to bedding). However, the anisotropy was not as marked as for the Mercia Mudstone (Jones and Hobbs, 1998b). It is clear from the results that samples WB1 and KM1, each with major kaolinite and minor smectite contents, are distinct in their behaviour from the rest.

5.2.4 Free swell test

Results for the free swell test range from 18 to 80%, the two highest values coming from samples NB2 and WB1. As the free swell test is a test on destructured soil, the primary influence on the free swell test results might be expected to be mineral composition.

Specific surface area is a useful indicator of clay mineral properties in terms of shrink/swell behaviour (Pearce et al., 1999). There is a positive correlation between free swell (FS) and specific surface area (SSA), but it is poor ($r^2 = 0.74$). A similar relationship is found for the two parameters for Gault clay (Jones and Hobbs, 1998a). However, the trend for Mercia Mudstone appears reversed (Jones and Hobbs, 1998b). Hobbs et al. (1982) also found a poor correlation between free swell and surface area for Cretaceous and Jurassic mudrocks from Harwell, UK. Oloo et al. (1987) found little correlation between free swell and Atterberg limit data, and recommended that free swell should not be used as a classifier of expansive soils. It may be that there is insufficient contrast in fundamental free swell behaviour between clay minerals such as illite, chlorite, and kaolinite (Taylor and Smith, 1986) and that the clay mineral montmorillonite behaves in a fundamentally different manner from these (Sridharan and Prakash, 1998). This was also suggested by the results quoted by Hobbs et al. (1982). No other significant correlations with the other parameters were found. However, the importance of free swell as a characteristic limiting water content with a well-defined controlling mechanism was emphasised by Sridharan and Prakash (1998). These authors define a 'free swell limit' as the boundary between the dominance of electrical forces ($w > FS$) and gravitational forces ($w < FS$). Their determination of free swell (Sridharan et al., 1985) is different from that of Holtz and Gibbs (1956), also described by Head (1992). The definition of Sridharan et al. (1985) is as follows:

$$\text{Free swell index} = \frac{V_d}{10} \text{ cc/g} \qquad \text{--6}$$

where: V_d is the swelled volume of 10g of soil

This compares with the definition used in this report (Head, 1992):

$$FS = 100 \frac{(V_2 - V_1)}{V_1} \quad \% \qquad \text{--7}$$

where: V_1 is initial volume of dry soil particles (10ml)
V_2 is the maximum swelled volume.

The free swell test was intended as a rapid guide to swelling potential, and not as a rigorous analysis (Holtz and Gibbs, 1956). Holtz and Gibbs (1956) and Komornik and David (1969) indicated a classification using the free swell test as follows:

Free swell (%)	*potential volume change*
>100	high
50-100	medium
<50	low

The above results place the Lambeth Group samples in the 'low' to 'medium' categories, samples NB1, KM1, and KM2 being in 'low' and the remainder in 'medium'.

5.2.5 Oedometer test

A total of ten (normal pressure) oedometer consolidation tests were carried out. These tests were done on undisturbed disc-shaped specimens, flooded at the start of the test (Anon, 1990). Following 1D consolidation under (24 hour) incremental dead-weight axial stresses, these stresses were incrementally removed, usually in two or three stages. This allowed the swelling behaviour under a reducing stress, P, to be examined. Results were expressed in terms of the swell index, Cs, defined as the slope of the rebound line on a voids ratio, e, vs. $\log_{10}$P plot as follows:

$$C_S = -\frac{\Delta e}{\Delta \log P} \qquad \text{--8}$$

Where: Δe is the change in voids ratio for a stress unloading increment, ΔP

Values of C_S from the normal oedometer tests ranged from 0.04 to 0.10. These values may be considered 'intermediate' and lie between those of the Gault clay and the Mercia Mudstone (Jones and Hobbs, 1998a; Jones and Hobbs, 1998b). There is a clear positive correlation. However, the scatter appears to increase with an increase in liquid limit. Head (1994) stated that the value of C_S (as with the value of compression index, C_C) increased with increasing liquid limit.

Values of compression index, C_C, ranged from 0.16 to 0.29. As was the case for the Gault clay and Mercia Mudstone, the values of compression index fell well below those obtained from the following empirical relationship with liquid limit for undisturbed clays (Skempton, 1944); that is, the measured C_C (oedometer tests) was always lower than the C_C estimated from the liquid limit:

$$C_C = 0.009\ (\text{LL}-10) \qquad \text{--9}$$

They also lay below those obtained from the following estimate for 'remoulded' clays (Skempton, 1944):

$$C_C = 0.007\ (\text{LL}-10) \qquad \text{--10}$$

Compression index correlates positively with swell index. Values of preconsolidation pressure, P_c', ranged from 272 to 820 kPa.

5.2.6 Heave potential

The concept of swelling or heave potential has been examined by many authors in order that laboratory index and swelling tests may be used in practical engineering situations to predict the heave of foundations. (Holtz and Gibbs, 1956; Van der Merwe, 1964; Komornik and David, 1969; Kassif and Ben-Shalom, 1971; Vijayvergiya and Sullivan, 1974; Basu and Arulananden, 1974; Obermeier, 1974; Snethen, 1984; Oloo et al., 1987; Sarman et al., 1994). These usually make use of plasticity, moisture content, and density and only one is based on work in the UK. Most reporters have found that liquid limit, moisture content, and dry density are the index parameters best correlated with swelling and heave.

In many cases, researchers have measured 1D swelling strain under a small surface dead load (Vijayvergiya and Sullivan, 1974). These gave a classification for swell strain of Beaumont Clay (Texas), under a 200 lb/ft^2 (» 10 kPa) surcharge, as follows:

%Swell strain 1D (10 kPa)	Heave potential
<1	low
1 to 4	moderate
>4	high

Direct comparison with the 1D swelling strain test used in this study is not possible due to the lack of a surcharge. On this scale the Lambeth samples fall into the 'moderate' to 'high' category if the surcharge requirement is ignored.

Another classification was given by Snethen et al. (1977) for USA soils as follows:

LL	PI	Initial suction	Potential % 1D swell strain	Class
(%)	(%)	(kPa)	(under overb. stress)	
<50	<25	<160	<0.5	low
50–60	25–35	160–430	0.5–1.5	marginal
>60	>35	>430	>1.5	low

The Lambeth Group clay samples fall in all three categories of this classification. An expansion potential scheme derived by Van der Merwe (1964), based on the Skempton 'activity' plot (Skempton, 1953) and its development by Williams and Donaldson (1980) is described in Taylor and Smith (1986) with respect to various British clay and mudrock formations. The Lambeth Group clay data were plotted in this manner (Figure 5). This plot shows that all the samples tested fell within the 'high' and 'very high' expansive potential class, over a range of 'activities' from 0.48 to 0.93.

As the result of a widespread study of the swelling properties of mudrocks in the USA, Sarman et al. (1994) produced the following classification scheme, based on swelling pressure, P_{sw}, and volumetric swelling strain, ΔV:

P_{sw} (kPa)	ΔV (%)	Swelling potential
>5000	>50	Very high
3000–5000	26–50	High
2000–3000	16–25	Medium
1000–2000	5–15	Low
<103	<5	Very low

This scheme places all the Lambeth Group clay samples tested into the 'very low' category.

The concept of 'effective plasticity index', a weighted average, has been described by the Building Research Advisory Board (BRAB, 1968) to deal with multilayered soils of different plasticity indices. Volume change potential has been defined more recently for over-consolidated clays, in terms of a modified plasticity index term (I_p'), in Building Research Establishment Digest 240 (BRE, 1993) as follows:

I_p' (%)	Volume change potential
> 60	Very high
40-60	High
20-40	Medium
< 20	Low

where: $I_p' = I_p$ x (% <0.425mm) / 100%

When the above modification was made to the Lambeth Group samples' test results, a reduction in plasticity index of up to 10 percentage points was obtained. By far the greatest reduction was for sample NB2. Most reductions, however, were less than 1. The classification places all the Lambeth Group samples in the 'medium' category (the BRE classification aims to eliminate discrepancies due to particle size where, for example, glacial till and other well-graded soils are concerned).

A host of schemes has been put forward, particularly in the USA, most of which use swelling and suction as their basis (Snethen, 1984). Sarman et al. (1994) concluded from an extensive study of US mudrocks that swelling was not related solely to clay mineral type, but also to pore-morphology. They found that bivariate correlations with swelling were unsuccessful. Pore morphology has not been examined as part of this study, and so comparisons cannot be made here.

In summary, the classification schemes described above, all place the Lambeth Group samples in 'low' or 'medium' categories for heave or swelling potential. Compared with the Gault clay and Mercia Mudstone, and with mudrocks worldwide, the swelling and shrinkage results for the Lambeth Group samples tested fall within a narrow range in keeping with their similar mineral composition and structure. However, the clay mineralogy does appear to have influenced some swelling properties, for example the samples with major kaolinite and minor smectite (WB1 and KM1) have a different behaviour pattern to samples with major smectite and minor kaolinite (NB2, *NB3?*, CF1, NH1, MM1, and EN1), with the possible exception of NB1. Table 6 summarises the swelling behaviour in terms of simple descriptive ratings.

5.3 SHRINKAGE RESULTS

The shrinkage test results are reported in Jones (2001) and shown, along with swelling and index data, in Table 4. Correlations between shrinkage parameters, and between shrinkage and index parameters, were examined. The spreadsheet correlation matrix (Table 5) was useful in this respect.

5.3.1 Linear shrinkage test (BS1377: 1990*;* Part 2*;* Test 6.5)

The linear shrinkage test results fall within a narrow range (12 to 16 %). The resolution of the test method does not allow a decimal place to be applied with any confidence. These results appear to be typical for British clay soils. However, higher values were reported for Gault clay (Jones and Hobbs, 1998a) and lower values for the Mercia mudstone (Jones and Hobbs, 1998b). (The greater the amount of shrinkage the greater the value of linear shrinkage).

$$LS = 30\ (SSA) - 272 \qquad (r^2 = 0.90) \quad \text{--11}$$

As far as correlations with other index parameters are concerned, the 1967 edition of BS1377 (BSI, 1967) gave the following relationship between plasticity index (PI) and linear shrinkage (LS) for clays:

$$I_p = 2.13\ (LS) \qquad \text{--12}$$

No correlation of this type was found between linear shrinkage and both plasticity index and liquid limit for the Lambeth data reported here. Correlations suffered from the small number of data points and the fact that the samples all had similar linear shrinkage and plasticity indices.

5.3.2 Shrinkage limit test

The volumetric shrinkage limit test (definitive method) is described in BS1377: 1990; Part 2; Test 6.3 (BSI, 1990). Values of shrinkage limit range from 6.9 to 17.5 % (n = 10). Samples MM1 and NH1 had the lowest and highest values, respectively. The range of maximum volumetric strain was high (6–17 %), CF1 had the lowest and NH1 the highest. The shrinkage ratio, R_s, (effectively the final dry density) was defined for a shrinkage limit test specimen as follows (Head, 1992):

$$R_s = \frac{m_d}{V_d} \qquad \text{--13}$$

(where: m_d is oven dried mass, and V_d is oven-dried volume)

Values of R_S ranged from 1.90 to 2.19. Details of the test method and results were given by Hobbs (1998). The shrinkage plots are generally irregular, the best of which were for samples WB1 and NB3 (Jones, 2001). Many test plots showed a pronounced volume 'low' followed immediately by a 'high' at or below the shrinkage limit. The reasons for this were unclear. However, such behaviour was described for kaolinite as 'residual swelling' by Yong and Warkentin (1975) and attributed to elastic rebound between particles, and has been observed in other tests on the Mercia Mudstone (Jones and Hobbs, 1998b) and compacted Gault Clay and Mercia Mudstone (Marchese, 1998).

Yong and Warkentin (1975) stated that a low shrinkage limit was usually associated with large volume change. Thus, an inverse relationship should exist between shrinkage limit and volumetric strain. No such clear relation was seen with the data reported here. However, too few data were available to establish such a relationship. Also, the contribution of 'undisturbed' soil structure to the shrinkage results was unclear, and the overall volumetric strain measured in the test is a function of the initial moisture content or degree of saturation. Loss of material from the test specimen and retention of mercury within the test specimen militate against the accurate determination of volumetric strain. This was evidenced by the maximum volumetric strain being achieved mid-test rather than at the end (oven-dried state) in some cases.

Whilst the British Standard (BSI, 1990) shrinkage limit test, BS1377: 1990; Test 3, does not preclude the testing of undisturbed clay specimens, the test would appear to be more suited to remoulded or compacted specimens of clay, preferably not subject to cracking during shrinkage. This limits the scope of the test considerably. The shrinkage behaviour of 'undisturbed' clay soils, and the errors involved in the test, will be influenced by soil structure, fabric, particle and ped (or crumb) size, and stress history. The shrinkage behaviour of 'undisturbed' clay soils is also likely to relate less directly to mineral composition and index properties than is the case for remoulded clays. Compacted specimens of high plasticity and tropical clays may exhibit cracking during shrinkage and be subject to the errors discussed above.

There appears to be no correlation between linear shrinkage (LS) and shrinkage limit (SL) for the Lambeth Group clay of the type described for Mercia Mudstone by Jones and Hobbs (1998b). The quantity 'shrinkage index', SI, also has been calculated. This is complementary to the plasticity index and may be defined as follows:

$$SI = w_L - SL \quad \% \qquad \text{--14}$$

Where: w_L is liquid limit % and SL is shrinkage limit %

Results for shrinkage index range from 33.0% to 46.5%.

6 Swelling and shrinking classification

6.1 SWELLING POTENTIAL

Four types of direct swelling test were carried out on the Lambeth Group samples. These were: 1D swelling pressure (Hobbs et al., 1982), 1D swelling strain (BSI, 1990), 3D swelling strain (ISRM, 1981), and free swell (Holtz and Gibbs, 1956). Of these, only the free swell test was carried out on a 'disturbed' specimen. The remainder were carried out on 'undisturbed' specimens obtained from block or tube samples taken in the field.

Descriptive swelling ratings are given in Table 6 for the four swell-related tests carried out. These are based on the classification schemes described in section 5.2. It is clear from the table that there is little agreement between tests; for example samples EN1 and NB1 have a 'very high' rating for 3D swell strain and a 'very low' rating for swelling pressure. All the samples tested gave a swelling pressure rating of 'very low', suggesting that either the rating scheme or the test itself does not suit these materials. The Lambeth Group samples probably represent a small zone within the global scale of mudrock swelling behaviour. Comparison of the Lambeth Group data with Gault Clay and Mercia Mudstone data (reported elsewhere) support this suggestion. Classifications for shrinkage potential follow a similar pattern (section 6.2). There appears to be no correlation with the three clay mineral groups described (Table 6). The two samples with the highest activity (mineral class C samples: NH1 and EN1) show no correlation with the four swelling tests, with the exception of 3D swell strain (EN1 only).

As appears to be the case with some of the shrinkage data, the swelling tests involving the measurement of strain, in either 1D or 3D, appear to be more successful as far as classification is concerned, than the tests involving a water content or a pressure measurement. However, a positive correlation between swelling pressure and 1D swelling strain and between 1D and 3D swelling strain suggest that more refined classifications based on the Lambeth Group, and presumably similar British mudrocks would be possible, given more data.

6.2 SHRINKAGE POTENTIAL

Descriptive shrinkage ratings are given in Table 6 for the shrinkage limit test and plasticity index data. These are based on the classification schemes described in section 5.3. The effects of shrinkage of fine-grained soils can be of considerable significance from an engineering point of view (Holtz and Kovacs, 1981). There have been few attempts to specifically quantify shrinkage potential, as distinct from volume change potential. Altmeyer, (1956) gave a **shrinkage** classification based on linear shrinkage as follows:

LS	Shrinkage behaviour
> 8 %	Critical
5 to 8 %	Marginal
< 5 %	Non-critical

The above classification places all the Lambeth Group samples (LS = 12 to 16 %) in the 'critical' shrinkage behaviour category. This classification is far too broad to enlighten the narrow range of linear shrinkages reported for the Lambeth Group.

An extract from an **expansion** classification, based in part on shrinkage limit, was given by Holtz and Kovacs (1981):

SL	Expansion behaviour
< 11 %	Very high
7 to 12 %	High
10 to 16 %	Medium
>15 %	Low

(The overlap of categories reflects dependence on factors other than shrinkage limit).

According to this classification, Lambeth Group samples (SL = 6.9 to 17.5%) ranged from 'low' to 'very high'. The volumetric shrinkage strain measured in the shrinkage limit test may be a better indicator for shrinkage potential than the shrinkage limit itself. However, this quantity is dependent on the initial degree of saturation of the test specimen lying above the threshold value below which significant shrinkage occurs.

High shrinkage potential soils may not behave very differently from low potential soils because environmental conditions in the UK do not allow full potential to be realised (Reeve et al., 1980). The National House-Building Council (NHBC, 1995) classified shrinkage potential as follows:

I_p (%)	Shrinkage potential
> 40	High
20-40	Medium
10-20	Low

where I_p is the plasticity index (=liquid limit - plastic limit)

The plasticity index for the Lambeth Group samples ranged from 23 to 36 %, placing all the samples in the 'medium' shrinkage potential class. The above classification forms the basis of the NHBC's 'foundation depth' tables. A summary of shrink/swell descriptive 'ratings' is given in Table 6.

A summary of descriptive ratings derived from the principal test data is shown in Table 6. In summary, two shrinkage potential rating schemes based on plasticity index results place all the Lambeth Group samples in the medium class, while a rating based on linear shrinkage places them in the critical class, and one based on shrinkage limit ranges them from low to very high. Whilst reflecting to some extent the variability of the Lambeth Group, this rating is probably misleading and does not appear to agree with ratings based on either swelling results or on index test results.

Table 6 Summary of shrink/swell behaviour ratings showing key mineralogies.

S/N	Min	**Free swell FS**	**1D swell potential**	**P_{sw} swell**	**3D swell (SL) shrink potential**	**Shrink A_c**	**Activity**	**NHBC I_p shrink potential**	**BRE I_p shrink potential**
WB1	A	Medium	Low	Very Low	High	High	Medium	Medium	Medium
KM1		Low	Low	Very Low	Very High	High	Medium	Medium	Medium
KM2	B	Low	Low	Very Low	Medium	Medium	High	Medium	Medium
NB1	C	Low	Moderate	Very Low	Very High	High	High	Medium	Medium
NB2		Medium	Low	Very Low	Medium	Medium	High	Medium	Medium
NB3		Medium	Low	Very Low	Medium	High	High	Medium	Medium
CF1		Medium	Low	Very Low	Medium	High	High	Medium	Medium
NH1		Medium	Low	Very Low	-	Low	Very High	Medium	Medium
MM1		Medium	Low	Very Low	Medium	Very High	High	Medium	Medium
EN1		Medium	Moderate	Very Low	Very High	Medium	Very High	Medium	Medium

Mineral group:
A **Kaolinite** / smectite
B **Kaolinite** / illite
C **Smectite** / kaolinite

A procedure to estimate shrinkage limit from the Casagrande plasticity plot has been described by Holtz and Kovacs (1981) as an alternative to actually carrying out the test. According to this procedure, if the sample plots on the Casagrande A-Line then the shrinkage limit should be 20 %. If above, the shrinkage limit should be **reduced** by the vertical difference in PI from the A-line, and if below it should be **increased** by the difference. Holtz and Kovacs (1981) claimed that this method was as accurate as the shrinkage limit test itself. When this procedure is applied to the test data for the Lambeth Group samples, there is no correlation between the procedure-derived shrinkage limit and the measured shrinkage limit (Table 7). Nor is there a correlation when results are separated according to the mineralogical groups (A and C) in Table 6. In all but two cases (EN1 and NH1) the estimated shrinkage limit exceeded the measured.

Table 7 Comparison of measured (BS1377) and predicted (Holtz and Kovacs, 1981) shrinkage limit value, SL.

Mineral group	**Sample no.**	**SL_{BS} % measured**	**SL % predicted**
A	WB1	9.9	18.2
	KM1	7.4	10.7
B	KM2	15.0	17.4
C	NB1	10.4	11.9
	NB2	13.2	14.0
	NB3	11.4	14.0
	CF1	9.2	11.9
	NH1	17.5	16.1
	MM1	6.9	14.2
	EN1	12.7	10.8

7 Conclusions

7 CONCLUSIONS

The various swelling data were of reasonably good quality, with well-defined swelling pressure and swelling strain curves, developing identifiable peaks for the most part. The 3D (unconfined) swelling strain test showed clearly the anisotropic behaviour in relation to bedding. A good positive correlation was obtained between 1D swelling pressure and 1D swelling strain test results. Due to the greater simplicity of the latter, it may be appropriate to infer pressure from strain given sufficient data with which to set up a correlation. Commonly applied relationships between swelling and plasticity index were not successful, probably due to the small variation in plasticity index throughout, and the small data set.

The quantity shrinkage index, defined here as the difference between the shrinkage limit and liquid limit, has been shown to be a useful parameter, possibly as fundamental as the plasticity index. The reason for its relative obscurity is the very limited use of any form of shrinkage limit test. The linear shrinkage test also provided what appeared to be reliable data, though the narrow range of values characteristic of this test does not lend it to classification or correlation with other parameters. The amount of shrinkage in the shrinkage limit test is not normally quoted, as it is a function of the initial saturation/water content. However, there is a good positive correlation between initial water content and volumetric shrinkage strain.

Two ‘shrinkage potential’ rating schemes based on plasticity index results (Table 6) placed all the Lambeth Group samples in the ‘medium’ class, while a rating based on linear shrinkage placed them in the ‘critical’ class, and one based on shrinkage limit ranged them from ‘low’ to ‘very high’. Whilst reflecting to some extent the variability of the Lambeth Group, this rating is probably misleading and does not appear to agree with ratings based on either swelling results or on index test results. The contrast with the NHBC and BRE ratings is particularly sharp. The lack of agreement between the ‘index’ test-based and ‘direct swell/shrink test’-based classifications is probably due mainly to the important difference between testing ‘remoulded’ and ‘undisturbed’ samples, respectively. For example, the ‘activity’ based classification may work for a fully reworked Lambeth Group soil, but not at all for the same soil in its natural state.

In summary, various classification schemes place the Lambeth Group samples in ‘low’ or ‘medium’ categories for heave or swelling potential. Compared with data for other clays and mudrocks worldwide, the swelling and shrinkage results for the Lambeth Group samples tested fall within a narrow range in keeping with their similar mineral composition and structure. However, the clay mineralogy does appear to have influenced some swelling properties, for example the samples with major kaolinite and minor smectite (WB1 and KM1), and major kaolinite and minor illite (KM2), have a different behaviour pattern to samples with major smectite and minor kaolinite (NB2, NB3, CF1, NH1, MM1, and EN1).

Table 6 summarises the swelling behaviour in terms of simple descriptive ratings. These ratings are either derived from the literature or are empirical and based solely on ‘in-house’ data. The swelling pressure rating is probably misleading, as the test result is dependent on water content at the start of the test. Nevertheless, the rating could be said to be correct for the natural state of the soil, if this can be taken as representative. Some samples have undoubtedly lost water in transit and preparation. If this were the case then the swelling potential would be even less in the field than measured in the laboratory.

It is clear that many of the ad-hoc classification schemes reported in the literature disagree with each other, at least as far as the Lambeth Group clay samples are concerned. Whilst it was not envisaged that reliable predictive indicators would be produced from a small number of comparative laboratory tests, it has been shown that useful correlations may exist. Some of these appear to be related to mineralogy, and others not. Correlations between geotechnical parameters have been made with the help of a spreadsheet correlation matrix for the Lambeth Group clay.

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